HIGH-EFFICIENCY BUNCHER SYSTEM FOR LINAC

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The ideal beam buncher for injection into a linac should have a single-slope sawtooth voltage waveform. Such a buncher bunches a d.c. beam into δ-function bunches, thus leading to 100% rf capture efficiency, but sawtooth waveforms are difficult to produce at high powers. A sinusoidal waveform buncher gives a capture efficiency of only ~2/3. Higher efficiency can be obtained by adding second and higher harmonics to approximate the sawtooth waveform, but with the addition of each higher harmonic the complexity and cost of the buncher system get progressively higher and the gain in efficiency gets progressively lower. The proposed buncher system is based on an idea introduced many years ago by Beringer and Gluckstern (R. Beringer and R.L. Gluckstern, Proceedings of the 1964 Linac Conference, MURA, p. 564.). However, to make it realistic and practicable their original idea had to be augmented and modified.

A single harmonic buncher bunches a 360° (linac phase) section of beam so that ~240° of it is contained in an rf bucket 90° wide. In fact, 180° of it can be contained in a bucket ~22° wide. The basic idea for the proposed buncher system is to cut the beam into 360° sections and send alternate sections through two different buncher cavities operating at half the linac frequency. Each beam section is, then, 180° in buncher phase. When bunched it should fit inside a bucket 22° wide in buncher phase or 44° wide in linac phase. The capture efficiency is, therefore, easily 100%. Beam loss occurs only during beam branching and recombining.

Beam Sectioning and Branching

As shown in Fig. 1, this is accomplished by a sinusoidal transverse deflector (wobbler W), a septum S, and two dewobbler $\bar{W}_1$, and $\bar{W}_2$. The beam is wobbled laterally at half the linac frequency by the wobbler back and forth across the septum, which deflects the beam sections on the opposite sides in opposite directions to form two separate branches. The half-wobble of the sections of beam in each branch is then annuled by a properly phased dewobbler operating also at half the linac frequency. Lens L (a symmetric quadrupole triplet) images point-to-point with unit magnification between W and $\bar{W}$ ($\bar{W}_1$ or $\bar{W}_2$) so that the cancellation between the effects of the wobbler and the dewobbler is straightforward.

To obtain clean sectioning the beam should be focused at the septum S by lens L and lenses ahead of the whole buncher system. Lenses L_1 and L_2 (identical to L except for aperture) then refocus the branch-beams at the buncher cavities B_1 and B_2. In the other plane the beams should also be focused at B_1 and B_2 to reduce the required aperture in the buncher cavities to a minimum. Since there is no other focal requirement elsewhere in this other plane, this should be easy to accomplish.

Beam Recombining

After the buncher the beams have sizable momentum spread, hence the transport lines must be achromatic. Lenses L_3 and L_4 (identical to L_1 and L_2) image point-to-point between $B(B_1$ and $B_2)$

and the recombining septum $\bar{S}$. If septum $\bar{S}$ and the bending dipoles D_3, D_4', D_5, D_6 have same dispersive properties (all magnetic or electrostatic) the arrangement shown in Fig. 1 is achromatic between B and $\bar{S}$. In this simple arrangement the dipoles are located at the foci of the lens and the bending angles at the septum and the dipoles are all equal in magnitude.

The branch-beams are focused at septum $\bar{S}$ so that the separation between the beams can be made small. The beams come out of $\bar{S}$ at small but non-vanishing separation and angle (not visible in Fig. 1) and cross each other downstream at C where a final recombining deflector (combiner C) is located. The combiner has a sinusoidal transverse field also at half the linac frequency and kicks the, now, bunched beams laterally on the peaks of the field to remove the remaining small angle between the beam bunches. The recombined branched beam, then, enters immediately into the linac. The buncher voltage is adjusted to optimize bunching at the combiner or, equivalently, at the entrance to the linac. The first 3 or 4 quadrupoles in the linac are used to match the transverse optics of the beam.

Parameters

We will demonstrate the practicality of the scheme by giving one set (not necessarily optimal) of parameters for the conventional injection of a 750 keV proton beam into a 200 MHz linac. Fig. 1 is drawn roughly to scale, except that the horizontal scale actually indicates the distance along the beam.

1. Quadrupole triplets

All triplets are optically identical and operate in the FDDF plane. To just demonstrate that they are physically reasonable we shall make the simplifying assumption of zero gap between the elements. Then the distance f from the ends of the triplets to the foci is given by

$$\frac{f}{\ell} = \frac{1}{k\ell} \frac{\cosh 2k\ell \cos 2k\ell}{\cosh 2k\ell \sin 2k\ell - \sinh 2k\ell}$$

and the distance g from the ends to the unit-magnification point-to-point locations is given by

$$\frac{g}{\ell} = \frac{1}{k\ell} \frac{\cosh k\ell \cos k\ell + \sinh k\ell \sin k\ell}{\cosh k\ell \sin k\ell - \sinh k\ell \cos k\ell}$$

where $k = \sqrt{\frac{|B'|}{B\rho}}$, and B' and ℓ are, respectively, the field gradient and the length of each element. Taking a modest $|B'|$ = 1.96 kG/cm and ℓ = 6 cm we get ($B\rho$ = 125.2 kGcm for 750 keV proton)

$$f = 6.0 \text{ cm} \qquad g = 42.8 \text{ cm} .$$

A nominal 750 keV p-beam has a transverse emittance of ~50π mm-mrad. A beam size of x_o = ±1.5 mm at a focus (waist, α_o = 0) corresponds to a Twiss parameter of β_o = 0.045 m. At the ends of quadrupole triplets L_1, L_2, L_3, and L_4 we have

$$\beta = \beta_o + \frac{g^2}{\beta_o} = 4.12 \text{ m}$$

and x = ±14.4 mm. An aperture diameter of 3.0 cm (pole-tip field = 2.94 kG) is, thus, adequate for these triplets. The aperture of triplet L has to accommodate both the beam width and the beam wobble. At the entrance of L

$$\beta = M^2 \beta_o + \frac{f^2}{M^2 \beta_o} \quad \text{with } M = \cosh 2k\ell \cos 2k\ell .$$

This gives β = 3.01 m and a beam size there of x = ±12.3 mm. Together with a wobble of ±2.0 cm at S or ±2.33 cm at the entrance of L this requires an aperture diameter of 7.2 cm and a pole-tip field of 7.05 kG for triplet L. Although this larger aperture is not needed for the other triplets it may be expedient to make all of them identical.

2. Bending dipoles

We shall assume here that all dipoles and septa are magnetic. A bending angle of θ = 0.3 rad is shown in Fig. 1 The required (field x length) is 37.5 kGcm which can be supplied by a 5 cm long dipole with a field of 7.5 kG. Dipoles D_3, D_4, D_5, D_6 should have an aperture of 2.5 cm (gap) x 3.0 cm (width) and parallel ends so as not to introduce additional focusing action in the bending plane. Dipoles D_1 and D_2 are twice as long (10 cm). Their aperture could be slightly smaller, but it would be simpler to make all dipoles with the same aperture.

3. Septa

These are double-sided pulsed current septa each 5 cm long and pulsed to a peak current of ~12 kA per cm of gap ($\perp$ to bending plane) to produce ±7.5 kG on opposite sides. Depending on the beam optics in this plane a gap of 2 cm is perhaps adequate. The aperture width of the upstream septum magnet S has to accommodate the beam wobble of ±2 cm in addition to the beam width and the orbit sagitta and must, therefore, be 3.0 cm on each side. The aperture of the downstream septum magnet $\bar{S}$ could be much narrower, but it may be expedient to make both septa identical.

Assuming the longest desirable beam pulse to be 50 μsec a half-sine pulse with a half-period of 500 μsec (1 kHz) will be adequate. For a double-gap magnet there is no force on the septum. The septum can be 2 mm thick and made of copper. The yoke can be stacked from the standard 14 mil transformer laminations. Fig. 2 shows a cross-section of the septum magnet. The ohmic heating of the septum is ~3 Joule/pulse. Even without cooling the temperature rise is only ~0.4° C/pulse.

With a peak beam wobble of ±2 cm the 2 mm septum intercepts ~3% of beam. Beam heating of the septum is negligible. When properly adjusted the beam-recombining (downstream) septum $\bar{S}$ should not be struck by any noticeable amount of beam.

4. Wobbler and dewobblers

These are lumped-circuit 100 MHz transverse electric dipoles. To wobble the beam ±2 cm at septum S the required deflection is ±54 mrad which can be produced by a 6 cm long dipole with a peak electric field of 13.6 kV/cm. The gap (in the bending plane) has to accommodate the beam width and the sagitta and therefore has to be 3 cm. This gives a peak voltage on the plates of 40.8 kV. The wobbler and the dewobblers should be properly phased to the linac and relative to one another.

To deflect the beam in the transverse direction the power required is very small. It may not be too difficult to produce a square wave form on the wobbler. In that case there will be no need for the dewobblers.

5. Combiner

At the exit of the recombining septum $\bar{S}$ the beam center lines are separated by ±0.25 cm (beam width plus septum thickness). An angle of ±10 mrad between the beams will make them cross at C, 25 cm downstrean of $\bar{S}$ where the combiner is located.

The combiner is a lumped-circuit 100 MHz transverse electric dipole similar to, but much weaker than the wobbler and the dewobblers. It is phased so that the beam bunches (the beams are optimally bunched at C) are deflected at the peaks of the field. To remove the remaining ±10 mrad between the beams one needs only a peak field of 6.0 kV/cm over a length of 2.5 cm. The gap should be 1.75 cm giving a peak voltage on the plates of 10.5 kV. The variation of the field near the peak of a sine wave over the beam bunch length of ±11° is negligible. Since the beams are optimally bunched at the combiner it must be located right at the entrance to the linac. Matching of transverse beam optics must, therefore, be accomplished by using the first 3 or 4 linac quadrupoles.

Again, it may be possible to produce a square waveform on the combiner. In that case the beams do not have to be optimally bunched at the combiner and the entrance of the linac can be moved some distance downstream of the combiner, thereby leaving space for quadrupoles to match transverse beam optics.

6. Buncher cavities

The right-hand-side of Fig. 3 shows the energy-phase of an optimally bunched configuration of a 180° section of beam. Straightforward geometry gives a minimum bunch length of 0.3815 rad = 21.9° after the point A at the peak field has gained $\Delta\phi = -\frac{1}{2}(\pi-0.3815) = -1.38$ rad in phase. At a given drift distance z after the buncher the phase gain at the peak field is

$$\frac{\Delta\phi}{\phi} = \frac{\Delta\phi}{2\pi\frac{z}{\beta\lambda}} = \frac{\Delta t}{t} = \frac{\Delta z}{z} - \frac{\Delta v}{v} = \frac{\Delta z}{z} - \frac{1}{2}\frac{\Delta\varepsilon}{\varepsilon}$$

where v is the velocity, ε is the kinetic energy, and for 750 keV protons non-relativistic formulas are entirely adequate. Because of dispersion $\Delta z \neq 0$, instead we have

$$\Delta z = -(g-f)\ \theta^2 \frac{\Delta p}{p} = -\frac{1}{2}(g-f)\ \theta^2 \frac{\Delta\varepsilon}{\varepsilon}$$

where g-f is the distance between D_5(or D_6) and $\bar{S}$. Altogether we have

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{-\Delta\phi}{\pi}\ \frac{\beta\lambda}{z+(g-f)\ \theta^2} \quad .$$

With $\beta = 0.04$, $\lambda = 300$ cm (100 MHz), $z = 134.6$ cm (between B_1 or B_2 and C), $g-f = 36.8$ cm, $\theta = 0.3$ mrad, and $\varepsilon = 750$ kV we get the required peak buncher voltage $\Delta\varepsilon = 28.6$ kV.

The aperture of the buncher cavities should be just large enough (~0.5 cm diameter) for the focused beam to pass through to reduce the energy spread in the beam caused by the transit-time factor. The buncher rf should, of course, be properly phased to the linac rf.

Conclusion

In principle, except for the ~3% loss on the upstream septum there should be no other beam loss through this buncher system and through capture into the linac rf buckets. In addition to the high efficiency, it is advantageous in some applications to have the beam loss, large or small, occur outside instead of inside the linac as it is the case for conventional bunchers.

Acknowledgement

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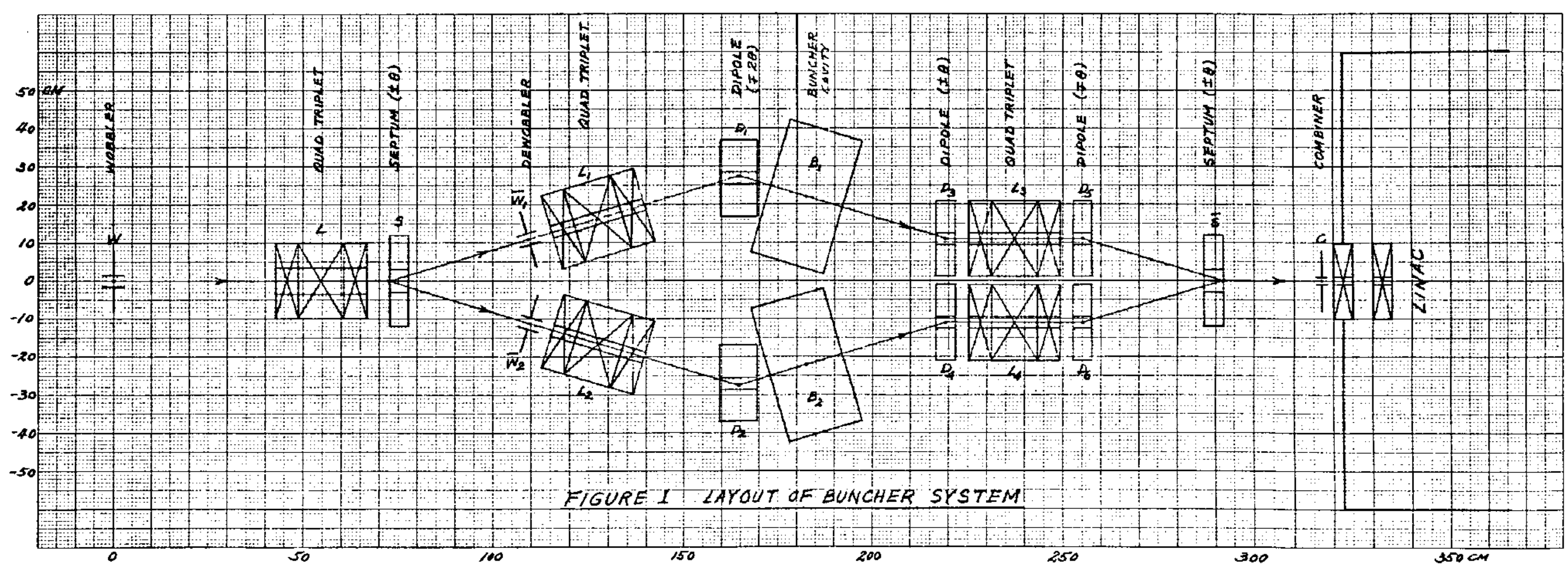

FIGURE I LAYOUT OF BUNCHER SYSTEM

K+E 10 X 10 TO ½ INCH 7 X 10 INCHES KEUFFEL & ESSER CO. 46 1320

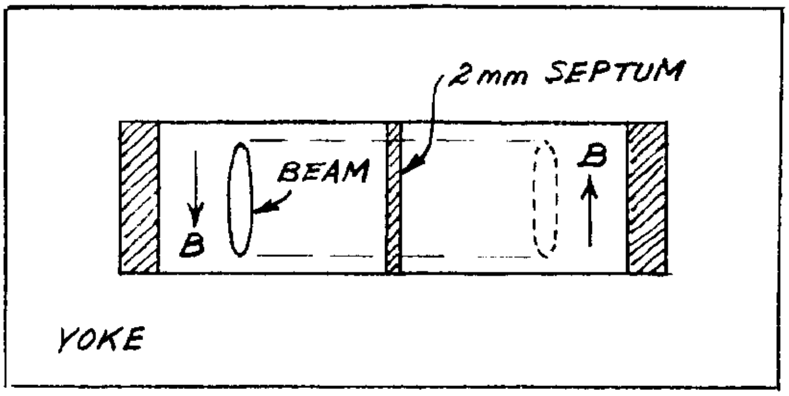

FIGURE 2 FULL-SCALE CROSS-SECTION OF SEPTUM MAGNET

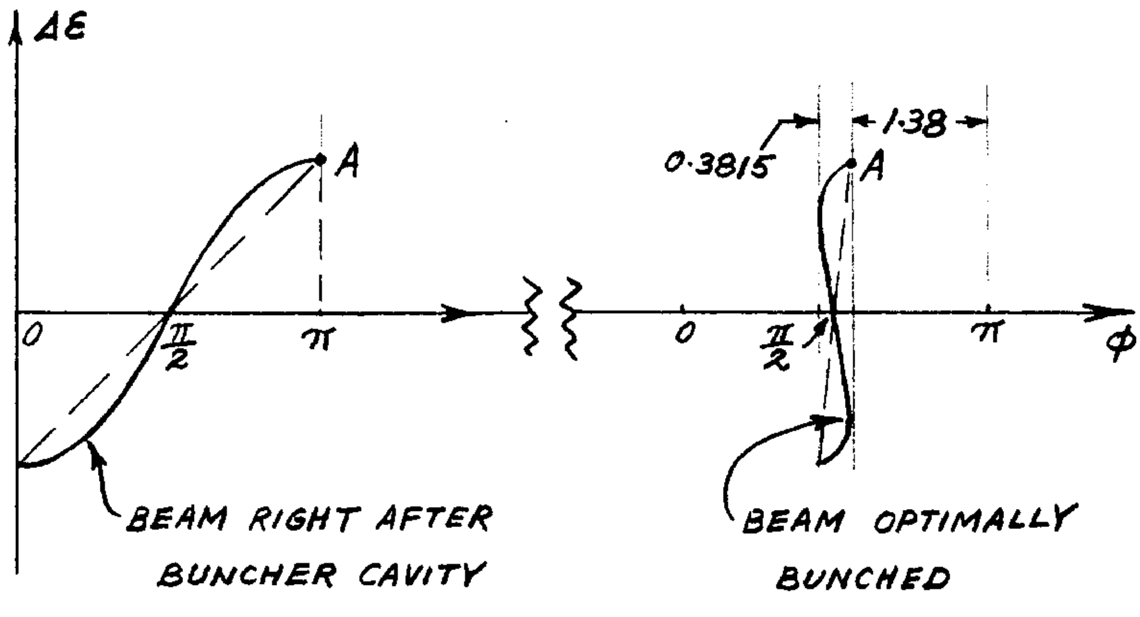

FIGURE 3 BEAM ENERGY-PHASE DIAGRAM